Eye Tracking in Child Computer Interaction: Challenges and Opportunities

Abstract

Eye trackers allow for the collection of eye gaze data. These data can include eye gaze points which are two dimensional Cartesian coordinates (x, y) that represent a point on a screen (for screen-based eye trackers) or points in a natural real-world environment (e.g., at home, school or a supermarket). Advances in eye tracking technology have resulted in less intrusive devices being developed that open up opportunities for the Child Computer Interaction community (CCI) to understand how children interact with digital technologies and offer new insights into their cognitive processing. This paper reports the results of a literature review of three digital libraries using the Quorom technique, to identify research on eye tracking that aligns with the core themes of CCI researchers. In total 66 papers were identified that related to the themes of design, education, programming and interaction design. The results highlighted that eye tracking studies with children have relatively small sample sizes (median *n* = 11) and that the median age of the children participating in the studies is 10.3 (inter-quartile range = 3.96). The metrics used within the research studies are predominately fixation duration and fixations within areas of interest. The paper contributes to a critique of existing methodological challenges to ensure quality data is obtained from studies involving children. In addition, the review identified that there are clear opportunities to further understand children's interaction with digital technology using other metrics such as pupillometry and blinks; these can assist to understand phenomenon including cognitive load and arousal which may be useful for user experience research.

Keywords: Eye Tracking, Eye Gaze, Children, Child Computer Interaction

1. Introduction

Eye tracking technology has evolved over the last century from mechanical optical hardware that was used prior to the emergence of electrical devices and computer software in the 1970s, to what is referred to as the third wave of eye tracking where commercial eye tracking products have become available [1]. These commercial products have facilitated the growth of research into eye tracking with children, as these are less intrusive and may cause less stress and anxiety for the children compared to early mechanical devices that were fixed to the participant's head. Within CCI research, the welfare of children is important and there is considerable literature critiquing the ethics of working with children [2,3]. The newer technologies such as Tobii Glass 3 and Pro Fusion enable data to be collected from children in a more natural and less invasive way than previous systems which make the use of eye tracking more appropriate. Some of the early studies on eye tracking with children in the late 70s and 80s were within the medical domain [4,5] whilst studies with children interacting with technology including robots dates back to the turn of the millennium [6]. The use of eye tracking or eye gaze data with children offers a great insight into the cognitive processing of information and a wide range of metrics can be captured to infer meaning around their interactions with the world.

Eye tracking involves the collection of eye movement data that relates to the visual stimuli that are processed by the brain. Within the context of CCI these stimuli may relate to the child interacting with computer screens, interactive toys, paper prototypes as part of participatory design sessions or other people within their social sphere. Researchers are often concerned with certain areas of the stimuli; this may be a line of text or a word [7] or whether the individual is making eye contact with a peer [8]. This data is then used to inform decisions about the child's cognitive processing based on theoretical hypotheses relating to the eye mind relationship [9] that postulates that when a person fixates on a stimulus they will continue to look at it until it is comprehended, and, as soon as they see a stimulus they will try to interpret it. This hypothesis has been challenged over the years [10] but is still widely used within some eye-tracking research [101,102].

The majority of current eye tracking systems are built around the use of infrared light, captured by cameras, that is reflected off the cornea in the eye (corneal reflection-based eye trackers). For example, the Tobii Pro Fusion system which is a portable eye tracker used for screen-based capture uses both bright and dark pupil illuminators for near infrared light to capture the eye movements from the pupil. Bright illuminators are usually centred in the optical axis directly where the person would be looking and cause the pupil to appear white whilst the dark illuminators are off axis. Other technology such as the Tobii Pro Glass 3 uses 8 illuminators in each lens to capture pupil movement. The versatility of modern eye tracking hardware enables studies to be performed within children's natural environments such as their homes, schools or clubs and community centres [11]. This provides researchers within CCI with opportunities to capture visual behaviour on a wide range of stimuli using metrics to advance the understanding of children and technology. These new insights may help shape the understanding of methods that are used to design and evaluate technologies for children.

Eye trackers allow for the collection of eye gaze data. These data can include eye gaze points which are two dimensional Cartesian coordinates (x, y) that represent a point on a screen (for screen-based eye trackers) or points in a natural environment. These points represent where the user has looked. Eye gaze points have been regarded as first order data [12] along with eye blinks and pupil diameter. These two variables (eye blinks and pupil diameter) are not commonly reported in eye tracking studies but they have been used to infer aspects about the user's cognitive and mental workload [54]. Nevertheless, most of the data that are used in eye tracking studies are fixations and saccades; a fixation is a position on the screen (or environment) where the user has focused their attention, and a saccade is the rapid movement of the user’s eye gaze between different eye gaze points. Fixations and saccades are used to provide a series of metrics that can be interpreted or be used to infer something about human visual processing or behaviour. Simple fixation-based metrics can include fixation count, total fixation duration and average fixation duration. Fixation count will simply inform the researchers of the number of times a user focussed their attention during a specific experience, and the average fixation duration (with standard deviation) will provide the typical amount of time that the user fixated or focused their attention. Other metrics such as fixation frequency can also be used to infer how often the user fixated per second (Hz) or per minute, for example, a high fixation frequency might correspond with the user being confused or because there is a lack of visual hierarchy in the user interface, or indeed for some other reason. Given that eye tracking metrics are quantitative, they can only tell us of ‘what’ happened but not ‘why’ it happened. Hence, studies using eye tracking datasets are sometimes complemented with explanatory data, for example an audio recording of the user’s voice during a concurrent think-aloud session, where the user verbally describes their experience at the same time as the researcher records their eye gaze [28].. Nevertheless, fixation-based metrics can be useful when used to compare and benchmark between several areas of interests (AOIs). AOIs are predefined areas (e.g., the navigation bar) that are determined by the researcher. For example, comparing AOIs can allow the researcher to infer the visual hierarchy of an interface [13]. There are metrics that relate to an individual AOI; visit count or visit frequency allows the researcher to infer how often the user returned to a specific AOI. Interpretation of such data has to be done with caution: if certain AOIs have a high visit count, perhaps that AOI is valuable, or it could be an area of in a decision making experiment [14].

The way a user navigates a system is of interest in many areas of HCI and CCI. When considering several AOIs, the researcher can also build a transition matrix which shows the likelihood of the next AOI given the earlier one. This path map can help understanding how a user navigates a visual interface [15]. There are other techniques such as Sequential Pattern Mining that the researcher can use to understand the temporal scanpath of the users’ attention. In eye tracking, the movement of the eyes between fixation is referred to as a saccade. Saccade metrics can include the number of saccades, saccade duration and also the regression rate. The latter is the number of times that the user regressed from right to left when reading text or computer program code for example.

Eye gaze data can be visualised as heat maps (akin to contour maps) which are basically attention maps showing which areas the user or a group of users provided the least and most fixations (or fixation durations, saccades or visits). Also, researchers may prefer to visually inspect videos of the users where the video is superimposed with eye gaze fixations, allowing for qualitative analysis of human behaviour. For example, Breen et al. [16] and McLaughlin et al. [17] used eye tracking videos to improve the training and teaching of healthcare professionals.

The remainder of this paper details the literature review that was carried out to describe the research to date that involved eye tracking research in CCI.

2. Methods

There were two phases to the review. The first phase (establishing themes) aimed to identify the key areas that the CCI community are publishing in, to classify papers. The second phase (literature review) was the gathering, reduction and then the analysis of publications between 2002 and 2020.

2.1 Phase 1 Establishing Themes

The starting point for the 1st phase of analysis was the themes identified by Giannakos et al. [18]. Giannakos et al. [18] performed a keyword analysis of papers in CCI between 2003 and 2018. This analysis resulted in 12 popular themes being identified. To ensure that the themes were still current, these 12 themes were used to code the 2019 and 2020 (until June) publications from the IDC conference and IJCCI journal. Using content analysis, the title and abstract of each paper was examined to determine whether it matched one of the published themes. The decision was made to allow papers to be classified to multiple themes due to the papers being interdisciplinary, for example the paper by Soleimani et al. [19] focused on tangible, learning and programming. Thirty-nine papers from the journal and 98 from the IDC conference were coded in this way. The results of this analysis are presented in table 1 below.

Table 1: Frequency of topics identified in the CCI Literature extending [18]

Popular Topics	Frequency 2003-2018 [18]	Frequency from IDC and CCI 2019-2020`	Total
Tangible	132	10	142
Participatory Design	103	2	105
Design	80	33	113
Education	79	32	111
Learning	80	31	111
Interaction design	66	24	90
Programming	64	20	84
Autism	58	2	60
Making	58	9	67
Mobile	57	13	70
Games	53	11	64
Educational Technology	47	14	51

Based on the coding performed in phase 1, it is evident that the themes were interrelated and so to enable the next stage of analysis it was decided to merge the related themes. Education, educational technology, and learning were merged to make a theme related to education, making and programming were also combined. Finally, to narrow the scope of the eye tracking literature review, any theme with less than 100 occurrences after merging were omitted which left six themes: Tangible, Education, Participatory Design, Design, Programming and Interaction Design.

2.2 Phase 2 Literature Review

The Quorom technique was used to conduct the literature review of eye tracking with children. To identify suitable papers, three digital libraries were examined: ACM DL, IEEE and Science Direct. The two core columns in table 2 were initially used to identify the potential papers. For example, eye tracking and children generated 299 papers in Science Direct compared 30 in the ACM DL. Duplicates were removed within each digital libraries, resulting in Science Direct n=370, ACM DL n=41, and IEEE n=140 contributing papers at this stage.

Table 2: Core words and themes used for the literature review

Core 1	**Core 2**	**Theme**
Eye tracking	Children	Tangible
Eye gaze	Kids	Education
	Child	Participatory Design
	Teenager	Design
	Young people	Programming
		Interaction Design

This resulted in a total of 551 papers being initially identified. Duplicates were then removed as were articles unrelated to children and computing and then the remainder were examined to ensure a fit to one of the six themes identified from phase 1. This process is shown in Figure 1.

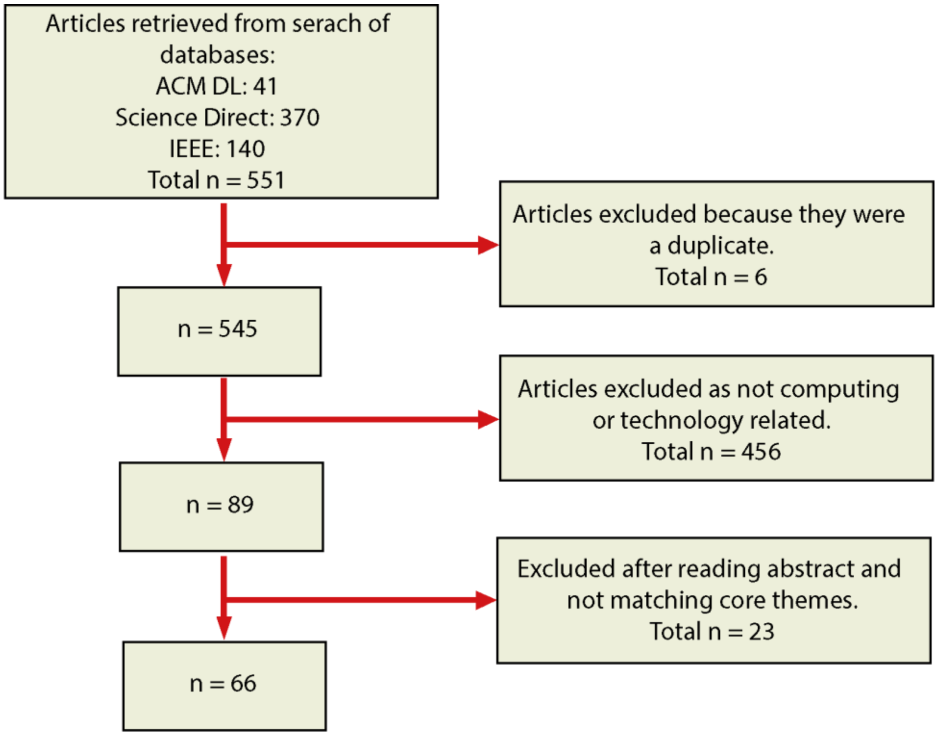

Figure 1: Literature Review Process using the Quorom technique

It was noted that there was no published work that was clearly related to tangible computing or participatory design. Papers removed at the last stage of filtering did not really match the themes, for example studies focused on the eye gaze data of the robot rather than the child. Descriptive data from the 66 remaining papers was recorded in Excel for analysis, this included information relating to sample size, metrics used, hardware type, research design and the age of any participating children.

3. Results

The results are presented in two sections; the first provides summary data relating to the 66 papers whilst the second section presents the key findings and identifies several key areas in which eye tracking has been used with children.

3.1 Quantitative Results

There were no papers that covered the use of eye tracking or eye gaze within tangible computing and participatory design, therefore this section focuses on the other four themes derived during phase 1 of the analysis. Figure 2 below shows the number of published papers relating to eye tracking and children between 2002 and 2020. This highlights the growth in research over the last 5 years of the use of eye tracking technology with children.

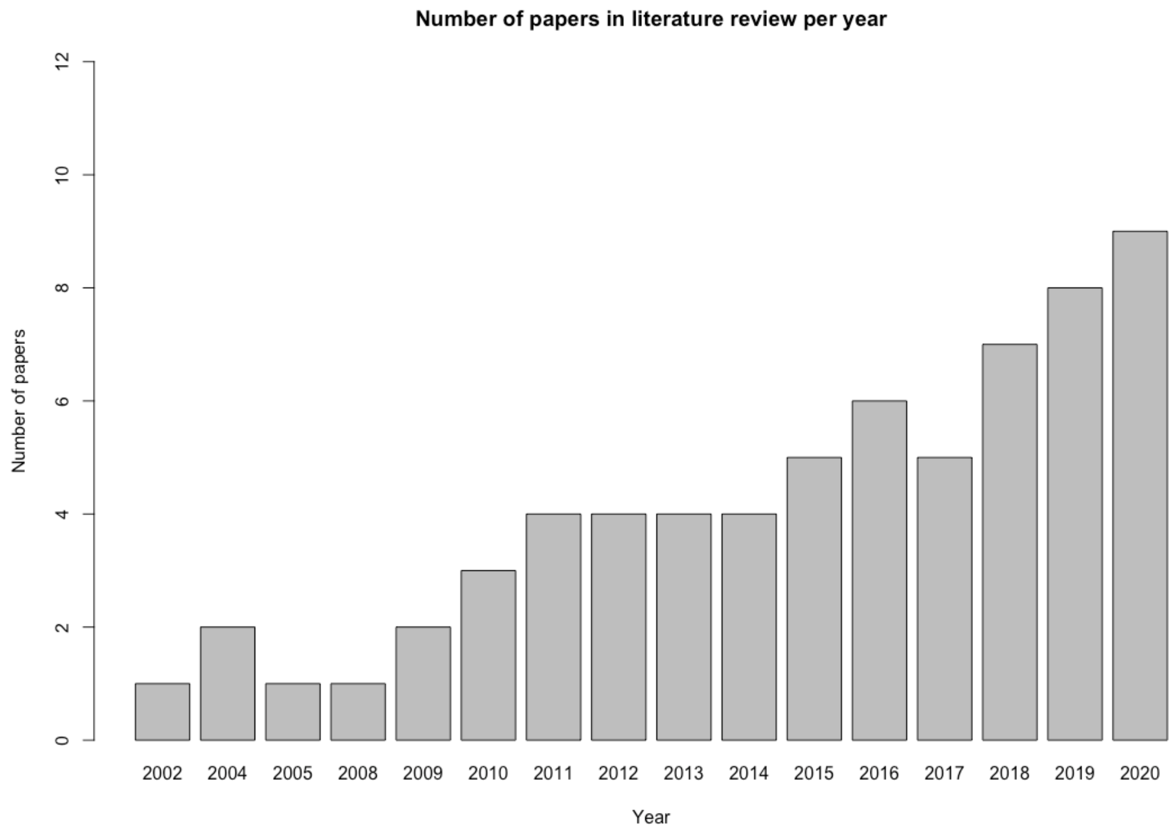

Figure 2. Number of published papers per year.

The median age of the children who participated in the studies was 10.3 and inter-quartile range is 3.955, as seen in figure 3. Not all the 66 papers had child participants using eye tracking hardware, some studies involved designing the eye tracking technology for children [70] or critiqued the use of eye tracking for children [20]. The median sample size was calculated for the 47 papers that had child participants, and this was 11 children. One paper was excluded as this was an outlier with a sample of 272 children participating in the study [77].

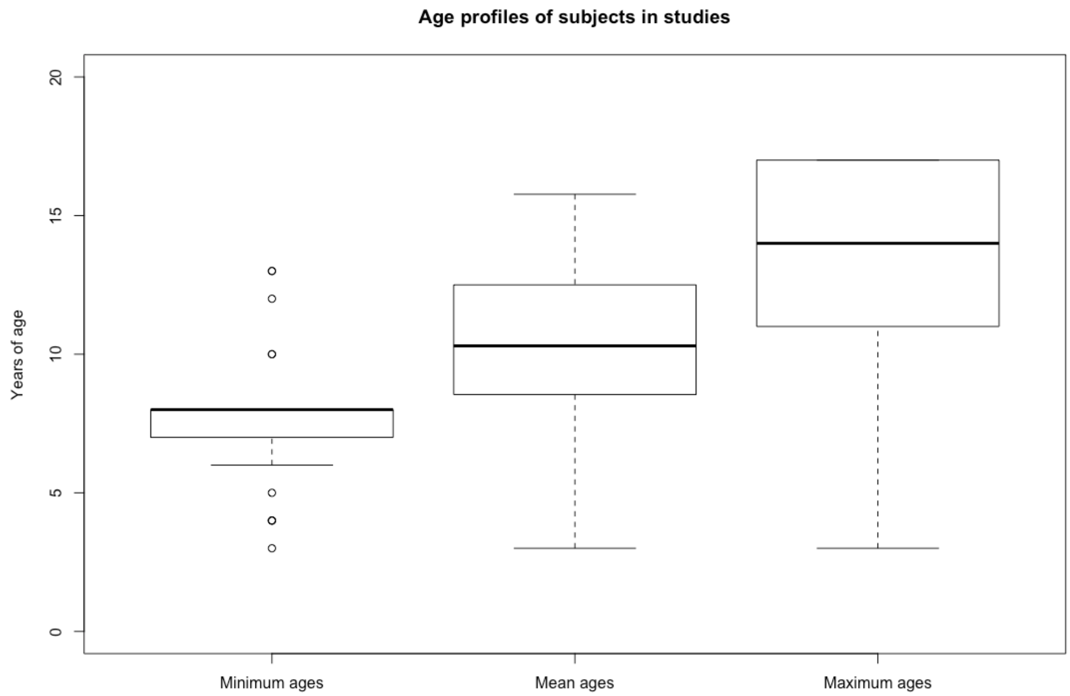

Figure 3: Age profiles of the children in studies using eye tracking

A large proportion of the research papers (n=28) focused on the use of eye tracking hardware with children with special educational needs. Children diagnosed with Autism were the largest group n=22. The remaining papers conducted studies with, or focused on designing systems for typically developing children.

To capture eye gaze data, 22 different models of eye tracking hardware were used. The brand that was predominately used within research studies was Tobii n=20, with 8 different models of their eye tracking hardware used, including screen-based hardware such as Tobii TX300 and T120, and Tobii glasses which have been used within programming along with SMI glasses [55-59]. There were 20 studies that used custom made technologies including web cams and Microsoft Kinect to analyse either eye tracking or eye gaze, predominately in the area of robot child interaction [67-72]. A large proportion of the studies, 29 out of 66 papers reviewed, use screen-based eye trackers from manufactures including SMI, Eyelink, Eye Tribe, Mirametrix and Tobii. Whilst there were 8 studies that used glasses from brands including Arrington Research [29,51], ASL Mobile [60] and Tobii and SMI [55-59]. Notably there was only one virtual reality eye tracker used, the Vive Pro Eye which was used in two separate studies [43 & 49]. It is clear that there is a diverse range of hardware used to support eye tracking research with children.

The eye tracking metrics reported in the 66 papers are shown in Figure 5, with fixation duration and the use of AOIs being the most prominent forms of analysis. Studies using saccade duration, pupillometry and blink rate metrics have not been used widely by researchers. The use of fixation duration and AOI analysis is fairly consistent across all four themes, shown in Figures

5-8, whilst gaze direction has predominately been used within interaction design research when examining child robot interaction [67]. Gaze plots and saccade durations have been used to examine children's behaviour within programming environments [58].

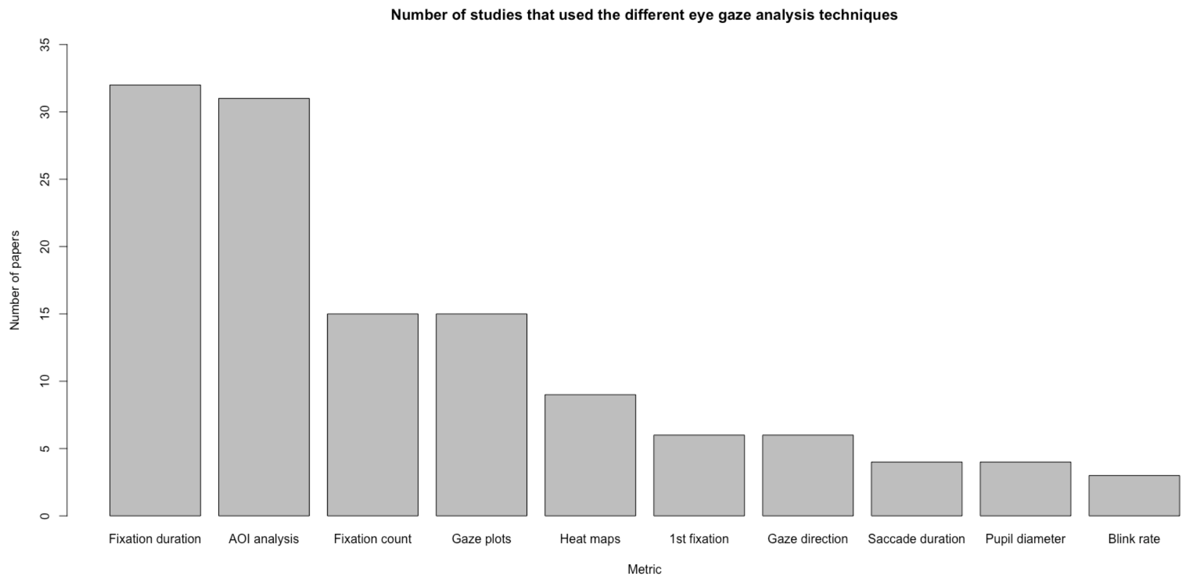

Figure 4. The frequency of metrics used in eye tracking or eye gaze with children.

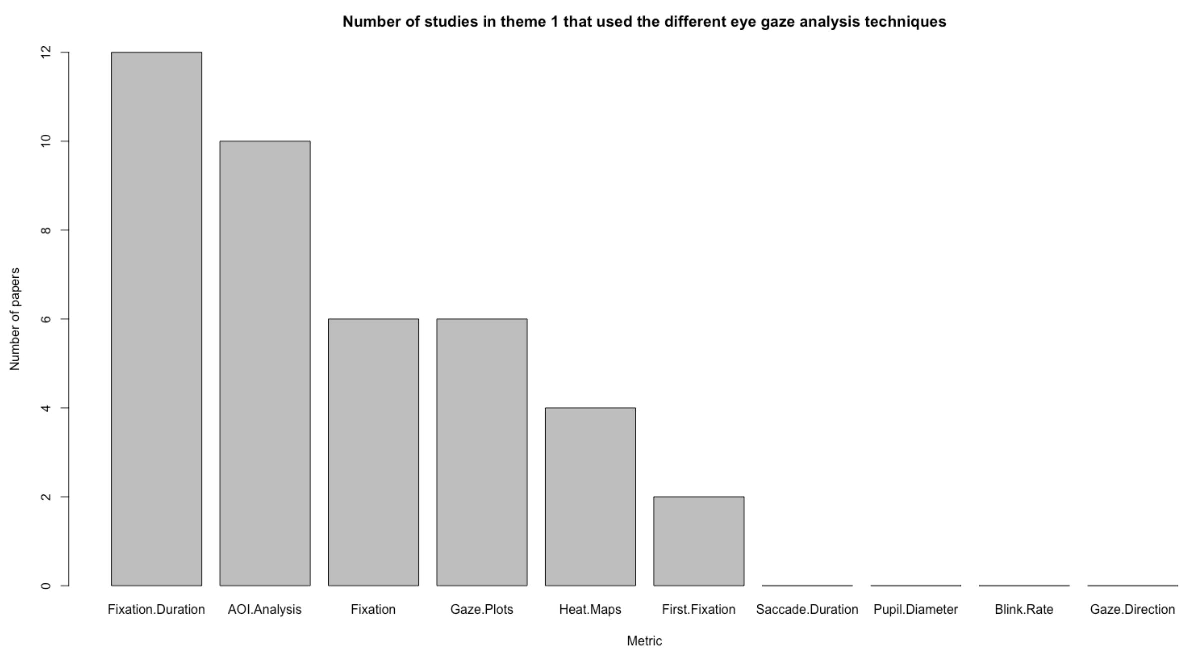

Figure 5. The frequency of metrics used in educational research using eye tracking or eye gaze with children.

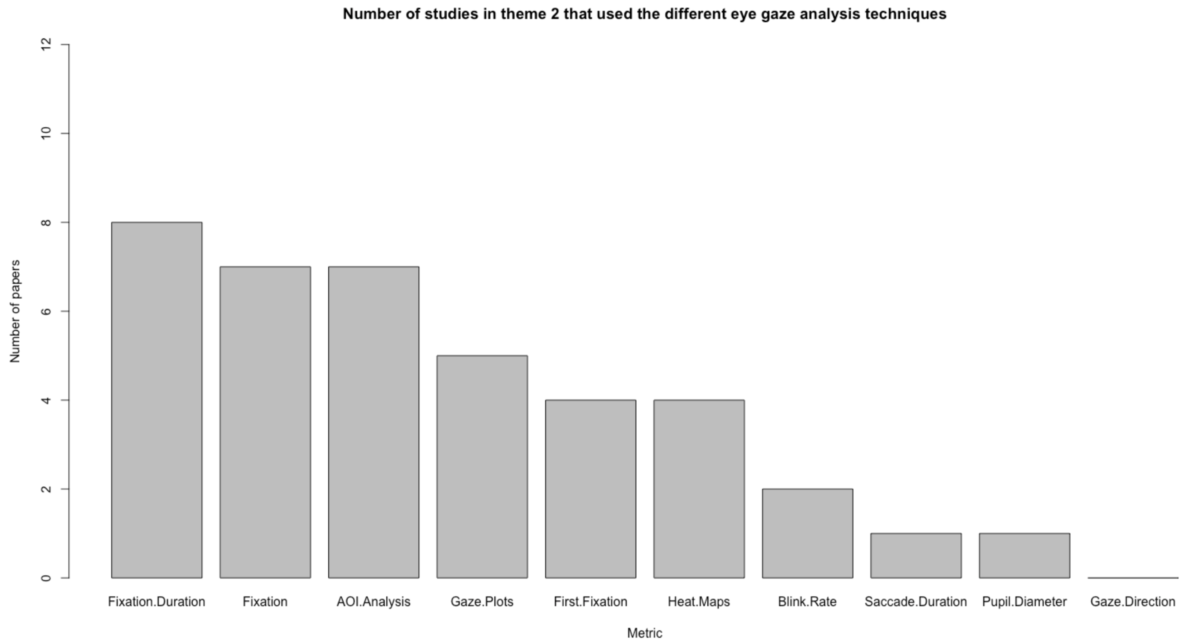

Figure 6. The frequency of metrics used in design research using eye tracking or eye gaze with children.

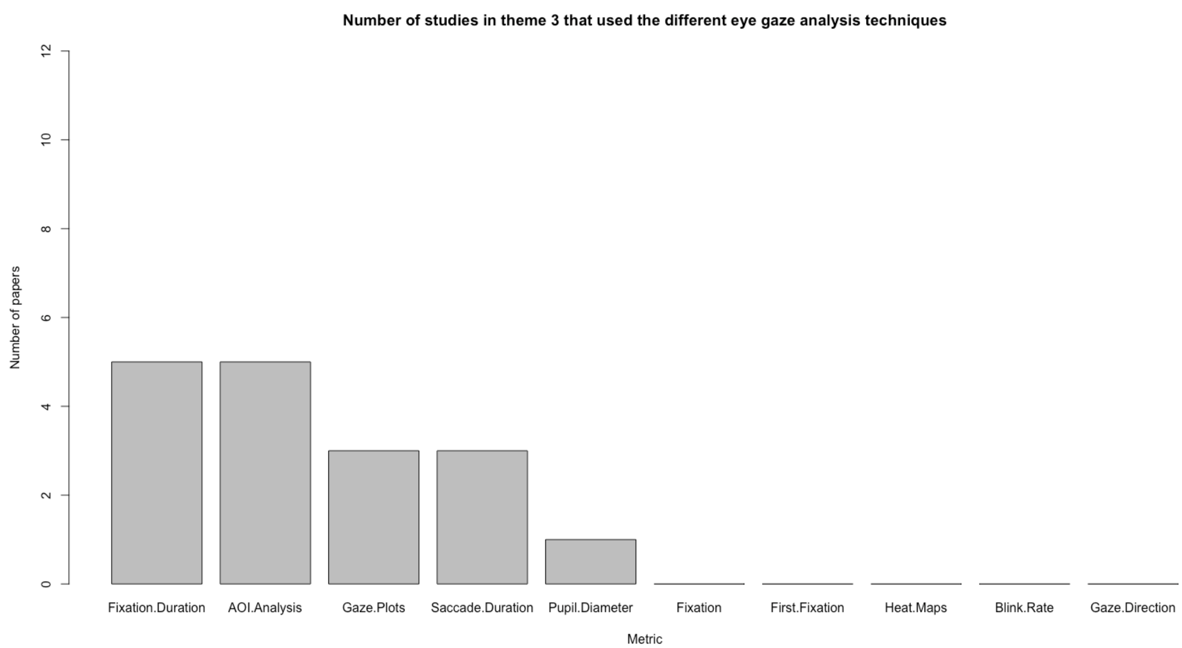

Figure 7. The frequency of metrics used in programming research using eye tracking or eye gaze with children.

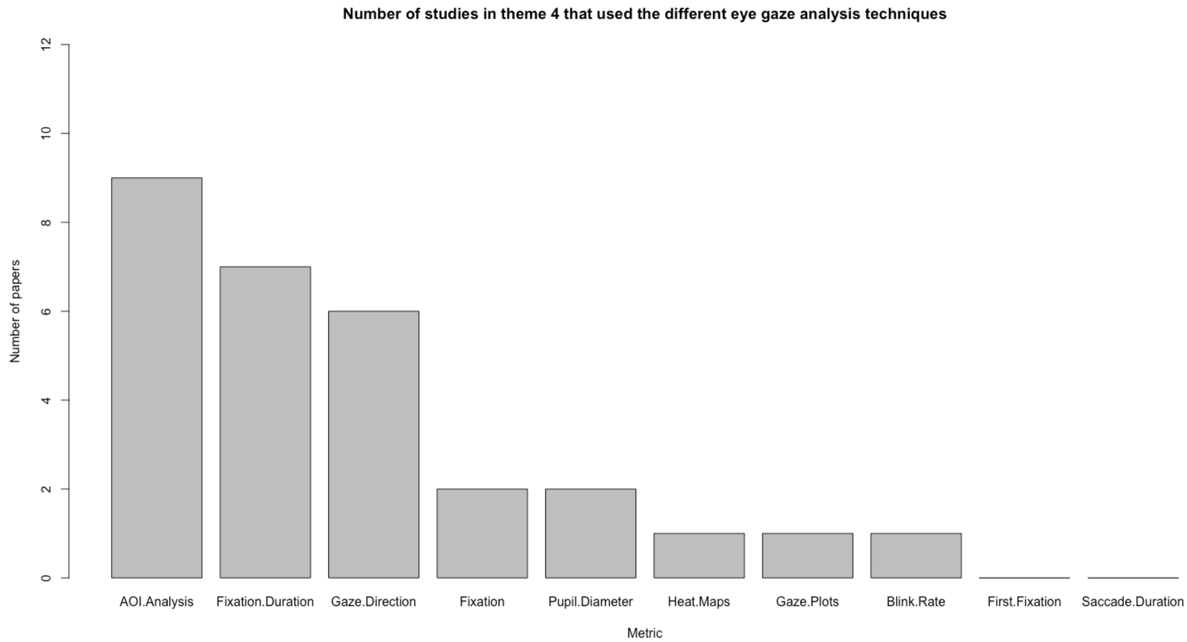

Figure 8. The frequency of metrics used in Interaction design research using eye tracking or eye gaze with children.

Three research / design contexts were seen; experimental studies n=28, user studies (this includes areas such as usability studies or product evaluations) n=18 and interaction design n=18. One paper was a theoretical critique of eye tracking practices and therefore was not classified to either category [20].

3.2 Research within Themes and Sub-Themes

From the analysis of literature, researchers have tended to use eye tracking technology in three different contexts the first as a form of interaction method within applications such as text to speech [31], interactive robots [65] or for experimental work comparing two products for example digital books [27] and finally user studies [33]. Within the four themes examples of interaction, user studies and experimental work will be discussed and critiqued.

Each theme, for which there were eye tracking papers identified, is examined here with sub themes being identified as they emerged from the literature review.

3.2.1 Education

This sub-theme consisted of 24 papers, with the majority of papers (n=9) classified as user studies, n=8 interaction design and the remaining (n=7) experimental studies. The experimental studies examined a range of different variables including gender differences [22], differences in reading between first and second language readers [31] and cognitive load within a math game whereby the visibility of the time pressure was manipulated between two groups [25]. There is clear scope for more empirical studies with children within an educational context.

Within the context of education, eye tracking studies relating to activities associated with interactive learning suggested following sub-themes;

- Searching and using the web [20-21],
- Supporting and understanding how children learn within a range of technologies [22-25],
- Usability and user experience of educational software [26-29],
- Understanding reading comprehension [26,30,31]
- Understanding the difference in learning between adults and children [32]
- Improving communication [33-36],
- Assistive technology and rehabilitation programmes [37-43].

Within an educational context, children are often using technology to assist their learning, through interactive content and searching online for material. Eye tracking studies have highlighted the fact that children have different search behaviours than adults, they explore the entire list of results before modifying their query, in comparison to adults who examine just the first line [21]. These conclusions were drawn from comparing adult's fixation data with children. Whilst all the adult's data was usable, only 11 out of 14 children's data could be used, the authors stated that the children were very agile and some of them moved too close to the monitor during the session, thus invalidating the data capture. The loss of participant data for these reasons have also been reported in other studies [24] who lost 12.7% of the trial data. The small sample sizes in these studies make generalization to other populations problematic.

To evaluate the usability of educational material eye tracking technology has been used in conjunction with other methods such as heuristics [26] and researchers have played back videos of eye tracking sessions to children to obtain verbal responses [27-28]. It has been suggested that in experimental studies within education, care needs to be taken in interpreting measures such as number of fixation or fixation duration, as the dynamic nature of the stimuli may influence the fixation patterns due to attention grabbing features such as animations [20]. In the study by [27] the time on task varied between the children and this may have been attributed to many factors including differences in reading abilities, developmental age, and level of engagement in the task. Thus, care needs to be taken when interpreting results of experimental data within an educational context. Researchers suggest that new methodologies specifically designed for children, maybe required [20].

Eye tracking and eye gaze data has also been used to assist children in their education, for example developing text to speech applications based on eye movement [30]. Apps have been developed to assist children with autism to communicate, and these have been evaluated using eye tracking to understand the children's visual attention [33]. Fixation data helped identify distracting content for the user, thus improving the usability. In the design of tutoring robots [36], experimental studies were performed looking at the contingency of interaction between an adult and a robot and a child and parent to help inform the design. The results highlighted the need for social cues to help facilitate the interaction, but the conclusions were drawn from a small sample of children n=12.

The focus of the research relating to assistive technology is through the use of eye tracking to evaluate new products to help children in a range of different contexts including within their home environment [40], speech therapy [38], redirecting the focus of children with ASD when viewing stimuli [42], and developing eye gaze attention determination algorithms [43]. However, not all studies used children in the design of the system [39, 43] and one used a mixture of adults and children in the evaluation [42]. The lack of child participation in the design and evaluation goes against the ethos of CCI.

There is clearly a body of literature where eye tracking has been used to understand how children interact with educational technology, but new methods appear to be required [20]. There is concern over the interpretation of data [27], the reporting of experimental studies with small sample sizes [36] and with data being excluded from experiments due to overactive children [21,24]. Eye tracking does however offer the opportunity to complement existing methodologies including think-aloud and survey responses to help improve and inform the design of applications for children.

3.2.2 Design

The design theme consisted of 10 papers, with n=6 experimental in nature and the remaining n=4 being user studies. Many of the experimental studies were examining the difference between children with autism and typically developing children when looking at visual stimuli, studies included examining emotional responses [48], identifying faces in images [44-45] and applying filters to draw attention to parts of the image [46].

Papers that may impact on the design of technology for children were included, as well as research using eye gaze to inform design. As a result, the these sub-theme emerged:

- Visual attention [44-48],
- Evaluation of designs [49-52],
- Storybook design [53],
- Cognitive load [54].

Visual attention is mainly focused on research with children with autism, for example face recognition [45, 48] and the development of systems that use filters to shift the gaze focus of a child whilst viewing an image [46]. Visual attention has also been examined within the context of children solving puzzle games [47] examining fixation location, fixation duration, saccades and saccadic duration. Results showed that the number of fixations increases with the level of challenge, but data should be complemented with other interaction records to aid the design. This further supports the use of mixed methodologies for use with children as identified in the educational theme.

Eye tracking can be used as part of an evaluation process to confirm the suitability of a product for children. These tend to be small scale studies, therefore the generlisation of the results to a wider population may be problematic. For example, researchers designed a robot [52] to assist children with autism, and a study was performed with 10 children to establish if the child imitated the actions the robot performed and paid attention to the robot. Fixation duration within defined AOI were used to infer differences. In a study examining Madeiran culture, a panoramic experience was evaluated with one child using Tobii eye tracking glasses to establish the areas the children were looking at whilst playing the game, these included the words of the song and other players [49]. Not all studies used small samples, 57 children participated in a study examining the visual layout of electronic books for kindergarden children [53] and finding revealed children focused on the print rather than the visuals when the words were highlighted during audio narration. When children are interacting with multi-model systems, they may encounter high cognitive load; this was examined with ten children within the context of video games [54]. In this study endogenous blinks and long eye fixations, greater than 600ms, were judged to be a measure of cognitive load. A comparison was made between the first and second play of the game demonstrating that cognitive load reduced over time as their performance increased. Eye tracking could therefore play a crucial role in understanding game design and the design of other applications providing that studies can be done with sufficient numbers to be at least partially generalisable

3.2.3 Computer Programming

Only a small number of papers (n=5) were found relating to computer programming and children, aligning to just three sub-themes:

- Differences in computer programming between populations [55,56],
- Attitudes to computer programming [57],
- Learning to do computer programming [58-59].

It is important to note that all the 5 papers identified within this theme were conducted with the same participants using eye tracking glasses and the data was examined in multiple ways by the authors resulting in five publications. The studies focused on understanding the differences in computer programming comprehension and attitudes between various demographic groups. In [55], they sought to understand the differences between children aged 8-12 and teenagers aged 13-17 in terms of learning to code. The research was conducted in a workshop where the children were developing digital robots. A mixture of eye tracking glasses from SMI and Tobii were used to establish time spent in AOI, transitions among AOIs and gaze similarity along with other research tools to measure attitude and learning. The children participated in a workshop that lasted between 45 to 90 min. It is not reported if the glasses were recalibrated during this period and therefore slippage or system inherent drift may have occurred, impacting the validity of the results. This is the first study identified that used multiple glasses in a collaborative context, other studies have tended to use one participant at a time. The data was then re-analysed to determine gender differences [56], differences in attitude [57] and differences in learning gains [58-59]. There is a large body of literature relating to using eye tracking in programming with adults, but this was really not the case with children.

3.2.4 Interaction design

In total there were 27 papers within this theme, consisting of n=10 experimental, n=7 design and n=9 user studies. Fifteen of the studies used custom built eye trackers or analysed gaze direction based on video footage captured from custom devices to perform the experimental work. Fifteen of the studies focused on children with special educational needs, notably children with autism. In line with other themes experimental work examined the differences between populations for example adult vs child in hand eye co-ordination [60] and the theory of mind in which 3 different groups of participants had to place objects on a set of shelves within a computerized application in order to examine theory of mind [76].

This theme focused on interaction design concepts such as input methods and gestures, sub-themes included:

- Hand-eye coordination [60],
- Using gaze as an input method [61-64],
- Robot and avatar Interaction [6, 65-75, 105],
- Evaluating interaction [76,77],
- Social interaction [29. 78-83].

One study focused on the differences between adults and children's hand eye coordination whilst playing virtual reality video games [60].This studies used ASL Mobile Eye glasses whilst the participants played a VR game within a Playstaion 2 which generated the VR world on a TV. This study was not using VR headsets such as the Vivo pro that has been used in other studies [43,49] and therefore it maybe worth replication.

The use of eye gaze for input has also been used to extend interaction capabilities with children using eye gaze to move the cursor [61,64] with this technique being applied to eye drawing [62] and Scratch programming [61]. This clearly offers new opportunities for designing eye-based interactions for children.

It is important to note that research has focused on eye gaze from both the child and the robot. For example, in the study [65] the researchers aimed to control and configure the eye gaze of the robot to demonstrate attentiveness. Many of the studies examine the use of robots to communicate or assist children with autism [67-70]. Low cost robots have been developed for diagnostic and treatment of autism [67] with built in gaze tracking capabilities, thus children's gaze direction can be tracked without the need of specialist eye tracking hardware like Tobii Glasses. Analysis of eye gaze was also performed with preschool children with autism within a classroom context, here a turn taking game with a robot was used [68]. In this study the number of times the child gazed at the robot was measured along with the duration of eye gaze. This type of analysis has been performed in other studies [69] where they manually coded whether the children were looking at the robot or not, inevitably this type of coding could clearly result in errors. Eye tracking has been used in studies were onscreen avatars have been used to communicate with children [65,74]. In the study by [74] children placed their head on a chin rest whilst interacting with an onscreen avatar to minimise the risk of data loss which has been reported in other studies [66, 79]. The use of chin rests may result in more accurate data capture but this may not be comfortable for children for a prolonged period of time. The majority of work has focused on diagnostic and treatment of children with autism and there is clearly more work required to understand how children interact with robots in a more playful context.

The study with the largest number of participants n=272, examined the effect of sponsorship disclosure times on whether children could understand whether social influencers videos were sponsored. Despite the large numbers the age profiles of the children ranged from 10 to 13 and the results may not hold true for younger or older children.

Whilst for social interaction the research has predominately focused on children with Autism and eye tracking has been used to understand the gaze behavior of children. For example, in the study by [78] a virtual reality platform was developed that included characters, their faces were defined with different regions of interest and the fixation duration within these was measured to understand how children reacted to characters. Many of these studies have been conducted to empirically answer a defined research question, for the CCI community there is a need to transform these results into accessible products for children.

4. Discussion

The literature review identified key themes and publications based on the Quorom method and highlighted some challenges associated with eye tracking with children. Some of the challenges identified are specific to children however, there are several reported issues that are not specific to children but are still important considerations when designing eye tracking studies. This section will focus on the challenges and opportunities for using eye tracking technologies with children. This section will extend the discussion beyond the papers identified within the literature review to identify opportunities within the themes that may be suitable for investigation with children.

4.1 Challenges

There are many challenges in running eye tracking studies with children as they can add an extra layer of complexity to the design of the research methodology, there are also technical challenges, both of which can impact on data quality. From the studies several key challenges were identified:

- Methodological challenges in interpreting data [20] and generalization of results due to small sample sizes (median 11 children).
- Loss of participants data through fidgety children [21, 24, 66, 72, 79], calibration issues [22] or needing assistance [72].
- Coding data and accuracy when using custom built eye trackers [67-69, 76].
- Potential issues in data quality including slippage, [28], system inherent drift [55-59], accuracy within the calibration processes [54].
- How to use eye tracking effectively in a collaborative context [55-59].

It was suggested that when children interact with educational technology new eye tracking methodologies may be required [20]. This goes beyond educational technology to all forms of eye tracking studies due to methodological challenges associated with the interpretation of results. For example, task completion time and fixation duration are measures that are used in experimental studies [27]. The differences between groups may be attributed to many factors including differences in reading abilities that may cause longer fixation durations and lengthen the time in an AOI. Therefore, it is essential that stimuli used within experimental studies are age appropriate to try and mitigate challenges of using fixation duration with emergent readers.

There is concern over the generalizability of results as many studies have used relatively small samples. Of the 28 papers that used an experimental methodology 11 used a sample of less than 40 children with the lowest being 10 children in 3 different studies. For example, in the study examining cognitive load [54] the sample was n=10, the ages of the children ranged from 6 to 8 and therefore the internal validity of the results could be questioned. In addition, the generalizability of these results to other games and populations remain uncertain. It is advisable that future studies reexamine some of the findings with larger and different population samples.

The review highlighted several cases where the children's gaze data was not captured from the hardware [21,24], as a consequence the child moving towards the screen. Researchers have tried to overcome this by using chin rests [74] and even car seats have been used for very young children [103]. It is questionable whether mechanical constraints would be comfortable for children, it may create extra anxiety and not represent their natural way of interacting with the technology. It is unclear how these studies communicated the loss of data to the child or reassured the child it is not their fault. This is important if the child cannot participate in the study due to calibration issues as reported in [22], whereby 3 children were excluded. It has been reported in previous studies using recognition based technology that children became anxious when errors occurred believing it was their actions causing the fault [100], it is conjectured that this may hold true within eye tracking studies. It maybe that children of a younger age are prone to be more mobile within eye tracking studies, but this has not been examined. In the study examining search behaviour [21] the children's age's ranged from 6 to 13 but it is unclear the age of the children who were reported to be more active. How to capture eye tracking data in a natural and less constrained way remains a challenge, partially solved through the use of eye tracking glasses, however data can be difficult to analyse if used with dynamic content.

Although the use of eye gaze in collaborative contexts with robots to establish gaze direction has been widely reported and researched [67-70], there are only a few published studies using eye tracking in a collaborative peer to peer context in programming [55-59]. Challenges remain from a hardware point of view when capturing data from a shared screen device, in the analysis of the data or synchronizing data from multiple streams if glasses are used.

The quality of the data can be affected by the hardware and this may be of concern within the 20 papers that used custom built hardware or relied on manual coding of eye gaze the data. There does appear to be a reliance on manual coding in experimental studies where gaze direction is captured [69, 71,72] and this could be prone to human error. Whilst there were 22 different eye trackers identified within this review many varied in their sampling rates, accuracy, and calibration processes. There may be a tradeoff between obtaining accurate data and ensuring the child can interact with the technology in a natural and unobstructed way. When examining the quality of the data obtained, there are a number of factors that may impact on the validity of the results, notably the accuracy, data loss and precision [84]. Many of the challenges of obtaining quality data are relevant to other user groups beyond children.

Accuracy is the difference between the true gaze position of the participant, in this instance a child and the recorded gaze position [85]. However, there is no real way of knowing the true gaze position and accuracy is normally established at the start of the study via the calibration process. For longer studies it may be essential to recalibrate to ensure accuracy as system-inherent drift can occur causing the data to be offset, this may have occurred in studies relating to programming [55-59] along with slippage if a child moved the eye tracking glasses. Maintaining accuracy is also challenging in screen based eye tracking studies. For example, in the study Al-Wabil et al. [28] they report an accuracy of 0.5 degrees, after a 5 point calibration process. The procedure presented in this study was calibration of the Tobii X120 eye tracker, followed by reading a digital book, completing the Smileyometer [28], reading a second digital book and completing the final Smileyometer. System-inherent Drift may have occurred between the two studies and ideally the eye tracker would have been recalibrated. In other studies the calibration process is not reported [54] and therefore there is uncertainty whether system-inherent drift may have occurred. Having the child recalibrate the tracker after every interaction with the stimuli may lengthen the study and therefore care needs to be taken to ensure the length is appropriate for the child and the process does not become to repetitive. Without appropriate calibration the quality of the data and results could be impacted leading to invalid conclusions being drawn. For example, dwell time is a metric that has been used in studies with children [55,78] and relates to the time gazed at an AOI. Research has shown that an inaccuracy of 0.5 can have a major impact on the dwell time, reducing it and removing an AOI all together [88]. Therefore, one of the key challenges for any experimental study using eye tracking with children is to ensure the accuracy of the tracker or risk the validity of the findings.

Data loss is also a concern within eye tracking and this occurs due to sampling discrepancies between the expected number and the actual number of samples taken. There are several contributing factors to this including, blinking, contact lenses, eye lashes, a child moving their head to look at a peer all of which prevent the camera from capturing an image of the eye. However, researchers may want to measure blinks to understand the child’s behaviour [54, 89]. The amount of data loss can vary between studies and it has been reported at around 25% in a gaze based study to predict children’s personalities when interacting with a robot [71].

The final parameter precision refers to the reproducibility of the measurement from one sample to the next. If precision is low then the number and duration of fixations can be influenced and this is important as many studies with children use these metrics [47, 54].

The issue of data quality is important when comparing differences between populations for example gender differences in programming [56], between younger children and teenagers [55] and adults versus children [21]. The concern is that differences in fidgetiness or irritability may lead to differences in eye tracking data quality, thus causing false differences to be identified [90]. For the CCI community understanding the issues around data quality is important and this should be reported within studies to demonstrate the reliability and validity of the findings. For example, in the research study looking at differences between children and teenagers the researchers used two different makes of glasses to capture eye movement [55], and with no data quality mentioned, the hardware differences may have impacted or influenced the results. Within this particular study, the AOIs were large and it may have only impacted on boundaries such as navigation icons that are adjacent to the next AOI. Other studies have reported the accuracy [28,91], however care needs to be taken as accuracy is often based on the manufacturers data obtained in ideal test conditions and in the real world the accuracy may sometimes be higher [92]. There are many challenges identified in obtaining eye tracking data from children, despite this there is a growing number of publications evidencing the effectiveness of modern eye trackers for use in studies with children. Researchers within CCI may harness this technology to investigate and better understand children's interaction with technology.

4.2 Opportunities

The review identified several opportunities for researchers to improve the methodology for working with children in eye tracking studies and potentially redesign the hardware. From the initial review it was identified that two of the main research areas in CCI, Tangible Computing and Participatory Design have not utilised eye tracking, there maybe opportunities within these themes. Opportunities that were identified include:

- With a median age of 10.3 there is need for research on effective ways to communicate and assist children and minimise data loss [21,24].
- Eye tracking in collaborative peer to peer contexts [55-59].
- There are opportunities to improve the ecological validity of studies by replicating them in the real world, for example robot interaction in the classroom or play scenarios [68,69].
- Replicating experimental studies with different populations or larger samples sizes [21, 39, 54]
- The opportunity to complement existing CCI methodologies such as the Fun Toolkit [47].
- Figure 5 identified a range of metrics and many are under utilized.

The median age of children participating in eye tracking studies was 10.3 years, with many studies working with children of a younger age [22,42, 53]. This presents methodological challenges, of how to assist children when interacting with the technology or enabling the children to work collaboratively. The CCI community could examine ethical ways of how to engage children in eye tracking studies to ensure quality data is obtained, children are relaxed and produce guidance on how to communicate errors within the calibration process and during the study. In [25] three children were excluded from the analysis due to distress or tiredness.

This is important especially as n=28 of the studies were with children with special educational needs.

Data loss could also be potentially addressed from a hardware perspective, but there is a potential tradeoff between obtaining quality data and the comfort of the child if constraining devices such as chin rests are used [74]. Using eye trackers with a higher sampling rate may offer the opportunities to capture more data to compensate for data loss. There is considerable variability in the sampling rate of eye tracking hardware used ranging from 60Hz [63] to a SMI RED500 with a sampling rate of 500Hz [77]. This would not alleviate the issue of looking away from the screen but offer greater confidence in the obtained data. Alternatively, the use of glass-based eye trackers would ensure that there are continuous streams of samples, unless they have their eye closed, which may minimize data loss from looking away from the screen when assistance is required. For this to be effective there also needs to be an easier way for researchers to synchronise the video stream with the pupil data, especially when used with dynamic screen-based content. Glasses can also be used within a wide range of physical locations and move away from studies in a controlled laboratory setting, to improve the ecological validity of findings.

There are clearly opportunities to improve hardware to facilitate collaborative studies as evident in [55-59]. One possible solution maybe the inclusion of facial recognition in screen-based eye trackers as part of the calibration process. Using facial recognition may enable eye tracking studies to be performed with children collaborating on a single device which would afford new research opportunities. It may be possible to calibrate the eye tracker to identify an individual's face and their eyes by using algorithms that are used in face recognition for authentication of users [104]. This would enable children to work in pairs or omit data from another person such as the facilitator who may be assisting the child to overcome difficulties.

Another opportunity is to replicate studies in a more natural environment for the child, such as their home or school. Experimental studies have been performed examining educational technology or software but there is concern over the ecological validity of the findings. Studies are often performed in labs [25] or a quiet room in a school [31] and how children interact may well be different in a classroom context when they are being influenced or distracted by their peers. This further supports the need to use eye tracking in CCI within a collaborative and natural setting.

Studies could be replicated in the area of programming, the papers that were identified within this theme were all with the same participants using the same programming environment [55-59]. The work was conducted within the visual programming environment Scratch. Many of the visual programming tools for children use bright colours to distinguish between programming concepts and research may be required to understand how children transition away from these environments. There is limited work on understanding how children program in comparison to adults and whether the same findings materialise within eye tracking research. For example, McChesney and Bond [98] examined computer program comprehension with people with dyslexia and the behaviours of the programmers was different to what had been previously reported in the literature. They suggested that further work is required to understand effects such as code layout, identifier naming and line length had on comprehension. Research has also examined how programmers identify errors [99] within code and this may be applicable to children to help inform curriculum design and support the development of computational and debugging skills. There are opportunities to really understand the barriers to programming with children by understanding the creation process and how they resolve errors. This could be vital as many countries push STEM agendas and are incorporating computer science into school curriculums.

Although design can be an ambiguous term [96], here the focus is on the opportunities for critiquing or improving the design of technologies for children which is the ethos of CCI. It has been recommended that eye tracking data compliments existing methodologies [47] and in some cases these could be used to further validate existing tools such as the Fun Toolkit which rely on subjective data. Within CCI design guidelines for children interacting with various technologies have been created from research studies, including electronic books [97] which is an area that has been examined eye tracking research [53]. Eye tracking studies could provide complimentary data to extend or validate existing guidelines or tools. When designing new products these have tended to be evaluated with subjective measurements with tools like the Fun Toolkit [86] and there is limited research using biometric data such as eye movement to compliment these subjective measures [28]. To validate the effectiveness of the guidelines experimental or user studies could be performed to understand how children interact with the technologies capturing data relating to Scan Paths, AOI, Fixation Durations. This data can provide insights into aspects such as the cognitive load [54], usability [33, 52] or provide information on what the child is interacting with through gaze plots. Eye tracking could be used to complimented CCI design practices, for example, Axelsson et al. [52] used eye tracking to understand how children interacted with a robot, following the use of participatory design sessions to help inform the design of the robot. There may be opportunities to understand how children interact with products or early conceptual designs using eye tracking data.

This review highlighted that there are opportunities to utilize a range of eye tracking metrics to further understand how children interact with the technology and the world. Fixation and fixation duration have been widely used, as shown in Figure 5, but other metrics may offer additional opportunities to generate new research questions relating areas including cognitive load and stress. Metrics including smooth pursuit, which relates to the motion of the eye when it follows a moving object, such as an animation [93], could be used to enhance understanding of children whilst playing computer games. It is possible to understand depth perception based around vergence eye movement, when an object moves towards the child, their eyes would rotate in to maintain fixation on the object. Other metrics that do not appear to have been used relate to pupillometry. This may be useful to understand aspects of user experience as it is associated with cognitive behaviours such as arousal, stress and cognitive load [94]. Pupil dilation can be used to establish which task is more cognitively demanding [95] and this may be useful for researchers examining constructs such as ease of use, which is often measured subjectively with tools such as the Fun Toolkit [86]. However, it must be noted that our eyes are more sensitive to changes in luminance and therefore care needs to be established to ensure differences between groups are not due to saccading from a bright area to a dark or vice versa.

Understand the metrics can help generate new research questions and examine theoretical models of child computer interaction in new ways.

5. Conclusion

In this literature review of eye tracking with children, 551 papers were identified from three digital libraries and using the quorum technique 66 papers were identified that align with current research trends in CCI. The median sample size within these studies is relatively low at 11 and this is very small for quantitative analysis of eye gaze metrics and results may not be generalisable. Given the large number of metrics, there can be false discoveries in small sample sizes if used for experimental work. There was only one paper identified that used a large sample n=272 of children aged between 10 and 13 [77]. Many of the papers that used small samples were for pilot studies and to perform usability evaluations rather than empirical studies. However there are clear opportunities to perform and replicate many of the studies with larger samples or different populations to establish whether the conclusions are still valid. It is also worth noting that data quality may impact on the ability to use results and therefore it may be necessary to recruit larger samples to offset any data loss.

When working with children there are numerous challenges that have been identified by the CCI community to ensure appropriate data is collected ethically. Eye tracking studies present challenges to ensure quality data is obtained. The accuracy of the data is important as this could be detrimental to the validity of any conclusions. For example, system inherent drift could occur in long studies without adequate recalibration or slippage if a child moves the eye tracking glasses. Developing appropriate methodologies and processes to mitigate these issues are still required to ensure quality data is obtained. This is especially important given the tendency to use small samples in eye tracking studies and children with special educational needs.

There are lots of opportunities to explore and replicate many of the studies that have been performed with adults with children, especially in the area of programming. There is a vast amount of literature that has explored issues such as gender differences, error detection and paired programming that could be examined with children. There are also many gaze metrics that have yet to be explored, that may offer insights into user experience when performing A/B experimentation or evaluation. Pupillometry and blink data can identify cognitive load or stress which may be useful for facilitators to intervene in research studies or provide quantifiable data about the mental effort a child exerts on a given task.

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